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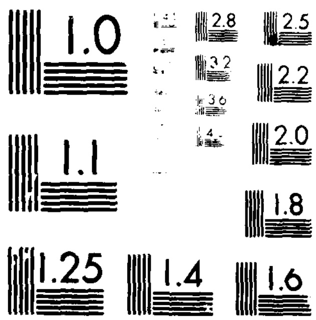

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SUMMARY OF THE AFOSR/MSU RESEARCH SPECIALISTS WORKSHOP ON COHERENT STRUCTURE IN TURBULENT BOUNDARY LAYERS*

LEVEL II

held at

Michigan State University

July 30 to August 1, 1979

BY

S. J. KLINE

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MECHANICAL ENGINEERING DEPARTMENT
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There was general agreement that progress towards a consensus of turbulent boundary layer structural information was made, and that the directions which future research work should take were clarified. Consensus/difference opinions, on a wide range of technical details, were recorded for both experimental and theoretical results. A number of long standing apparent discrepancies were resolved. However, it became clear that for some important matters

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neither consensus nor difference opinions could be established because there was only one investigator reporting results. There was general recognition that a number of different coherent motions exist in the boundary layer, and that different techniques (both visual and probe) emphasize some at the expense of others. It is necessary to determine what role each of the coherent motions play, as well as the importance of the interactions between these motions. Substantial progress has been made, but a consensus emerged that more overlap of techniques and objectives is needed, and that more experiments which combine flow visualization with quantitative measurements should be performed. Three different theoretical approaches were discussed. Each qualitatively simulated the occurrence of some of the observed structural features, via their underlying mechanisms. It is not yet clear how experiments will be performed to ascertain the relative importance of the various mechanisms, however a few features were elucidated that could be subjected to experimental check. At this stage, none of the theories can be considered complete or predictive. Some potentially important qualitative correspondences were made between numerical large eddy simulations and recent wall region data, although the computations still suffer from resolution, and perhaps spectral leakage problems.

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ACKNOWLEDGMENTS

We want to gratefully acknowledge the financial support of the Air Force Office of Scientific Research. Particular thanks are due to Lt. Col. Lowell Ormand for his insight with respect to the needs of the community working in turbulent boundary layer structure, and his willingness to support the innovative format of the workshop.

Thanks are also due to Dean Von Tersch of the College of Engineering of Michigan State University for additional financial support and encouragement.

The task of running the workshop was greatly facilitated through the help of several MSU students. Special thanks are due to Mr. Wendel Burkhardt, Mr. John Calkins, Mr. Brian Leary and Mr. Jeff Lovett of the Mechanical Engineering Department.

We want to acknowledge the sincere spirit of cooperation shared by all of the participants of the workshop. Special thanks go to Professor G. M. Lilley who at very short notice assumed the job of moderator for the entire workshop, and did a splendid job.

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ABSTRACT OF TECHNICAL PROGRESS

There was general agreement that progress towards a consensus of turbulent boundary layer structural information was made, and that the directions which future research work should take were clarified. Consensus/difference opinions, on a wide range of technical details, were recorded for both experimental and theoretical results. A number of long standing apparent discrepancies were resolved. However, it became clear that for some important matters neither consensus nor difference opinions could be established because there was only one investigator reporting results. There was general recognition that a number of different coherent motions exist in the boundary layer, and that different techniques (both visual and probe) emphasize some at the expense of others. It is necessary to determine what role each of the coherent motions play, as well as the importance of the interactions between these motions. Substantial progress has been made, but a consensus emerged that more overlap of techniques and objectives is needed, and that more experiments which combine flow visualization with quantitative measurements should be performed. Three different theoretical approaches were discussed. Each qualitatively simulated the occurrence of some of the observed structural features, via their underlying mechanisms. It is not yet clear how experiments will be performed to ascertain the relative importance of the various mechanisms, however, a few features were elucidated that could be subjected to experimental check. At this stage, none of the theories can be considered complete or predictive. Some potentially important qualitative correspondences were made between numerical large eddy simulations and recent wall region data, although the computations still suffer from resolution, and perhaps spectral leakage problems.

PREFACE

The subject of coherent motions in turbulent boundary layers has received much attention. Progress made using visual techniques and point measurements has resulted in a myriad of flow field descriptions, and suggested mechanisms, because of the enormously complicated three-dimensional, unsteady problem, with its multiple length and time scales. Several attempts have recently been made to obtain consensus or establish differences that need to be resolved. The first took place at the AFOSR Lehigh Workshop (May 1978) in the Morkovin B committee. An unpredictable result of that meeting was the agreement by several attendees to sit face to face around a table and record consensus and differences about the physical nature of experimentally observed structural aspects of the turbulence production process, and to determine the relationships between the various physical, theoretical and numerical models.

For several members of the group involved in the conversation, the Lehigh Conference had once again seen several competent and detailed investigations presented, as well as summaries of the current understanding of several groups of investigators, without the needed inter-investigator, inter-group synthesis and/or critical discussion of apparent consensus and differences. The reasons for this are profound. They were recognized by the organizers of the Lehigh Workshop in which solutions were given explicit form in the subcommittees. They were appointed and met to reach consensus on various turbulent boundary layer aspects. However, there was unanimous agreement among the scientists that a necessary degree of consensus had not been established on many important questions owing to lack of time for this specific purpose. The time required is much larger than intuition would suggest.

A new element that sparked the discussions was the sense of convergence towards agreement between experimentalists and between experimental and theoretical work, which resulted from

the short subcommittee sessions, but the facts certainly were not all flushed out. The result of this feeling, however, was the unusually cooperative atmosphere which led to the decision to arrange a meeting at Stanford University within a couple of months to see if consensus and differences could be more sharply delineated.

The meeting was held on July 24-26, 1978, in the Thermosciences Division of the Department of Mechanical Engineering at Stanford University. Steve Kline served as organizer. The major result of the meeting was a careful probing of the data during which time attempts were made to separate facts from models and speculations, with the objective of finding the commonality and differences that might focus the next round of research. Although a decisive consensus of the types, sequence of, and strength of events which result in the production of turbulence near a wall was not arrived at, the path which will eventually lead to the answers was cleared and straightened. A summary of that discussion is included herein. It was generally agreed that the meeting was extremely fruitful, and allowed interactions that did not take place at conventional meetings, owing to the lack of sufficient density of researchers, time pressures and the presence of too many individuals who are not au courant with details. It was decided to continue the efforts a year later at Michigan State University.

The three day workshop was held from July 30 to August 1. A summary of the results of the MSU Workshop are presented herein. Every effort was made to invite a balanced representation of active experimentalists, theoreticians and numerical simulators. The size of the group was purposely limited to about 15 participants. The format was informal, there was only one session at any given time and all participants were asked to attend all of the discussions. The proceedings were recorded both on tape and by three graduate students. The objectives were to arrive at and record the consensus/difference opinions of the major research groups involved in the investigation of coherent motions in turbulent boundary layers. In

particular to:

1) Reconcile or establish differences in observations and suggested mechanisms of wall region structure.
2) Reconcile or establish differences in observations and suggested mechanisms of outer region structure.
3) To critically evaluate the evidence and suggested mechanisms for outer/wall region interactions.
4) To establish direction for future experiments.

The nature of the output of these meetings is sufficiently different from conventional research reports, that we have decided to make the format of presentation of results one of statements of consensus/differences and questions. A presentation of the background of each statement would have made this report into a monograph and, we feel, lose its impact. This probably does limit the audience to readers actively working in the field. To allow a wider audience to gain from the proceedings, Appendix 1979E has been included. It is a current review of turbulent boundary layer structure. Appendix 1979A will give the reader some idea of the range of questions discussed, some of which remain to be examined in more detail.

TABLE OF CONTENTS

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PROGRAM

Monday July 30

8:30	Registration, coffee and donuts
9:00	Welcome and overview of workshop
9:15	Discussion and modification of this schedule
9:45	Review of nomenclature
10:30	Break
10:45	Questions to be addressed
12:00	Lunch at Kellogg Center
1:00	Wall layer structure - Tiederman
1:30	New data - Hanratty
2:00	New data - Falco
2:30	Discussion on questions begins
3:30	Break
3:45	Movies
4:00	Discussion on experimental data continues
5:00	Session ends

Tuesday July 31

8:45	Coffee and donuts
9:00	Movies
9:15	Discussion on experimental data continues
10:30	Break
10:45	Movies
11:00	Discussion on visualization and measurement techniques
11:30	Streamwise vorticity measurements - Willmarth

12:00	Lunch at the Kellogg Center
1:00	Formulate consensus/difference experimental matrix
2:30	Suggest critical new experiments
3:00	Break
3:15	Movies
3:30	Theoretical models
4:00	Presentation - Walker
4:20	Presentation - Hanratty
5:30	Session ends
8:00	Dinner

Wednesday August 1

8:45	Coffee and donuts
9:00	Continued discussion of theoretical models
10:00	Numerical simulations - Moin - recent results of large eddy simulations
10:20	Discussion on interaction between experiments, theory and simulations
10:45	Break
11:00	Conclusions
12:00	Lunch
1:30	Demonstration of boundary layer in smoke tunnel, and video taping experiments

A. Review of the Stanford Workshop

The workshop commenced with a concise summary of the first Coherent Structure Workshop held at Stanford University in July 1978 by Steve Kline.*

I. General

Most important single result is establishment of an appropriate cooperative forum for work needed to facilitate progress on the boundary layer structure problem. This forum focuses on:

(1) agreements among various laboratories - point by point

(2) Apparent disagreements among laboratories

(3) Experiments to clarify (2)

Why is a new forum needed? The issues (events) in turbulent shear layers are too complex for adequate discussion within the time schedules of conventional meetings. It requires a very long time to record views on each point, exchange information in full depth, and thereby reach resolution sufficient for orderly planning for further research.

II. Preliminary Groundwork

A. Semantics to facilitate accurate communication: attached as Appendix 1978A.

B. Appropriate non-dimensional scales: attached as Appendix 1978B.

---

*Continuation of the work of the "Morkovin B" Committee from the 1978 Lehigh Conference.

III. Specific Results

Results of discussions on experiments are organized under three topics: wall layers; outer layers; wall/outer layer interactions.

A. Wall Layers: Statements

1) Low & high speed streaky structure always exists; it is the dominant observed features in the zone $0<y^+<7\text{-}10$. See Kline Lehigh paper.

2) a 3 or 4 part process is observed: streak migration, lifting, apparent oscillation; breakdown.

3) $\lambda^+ = 100$, $\lambda^+_{mode} = 80$ (uniform among all groups reporting), x^+ of oscillation phase $\simeq$ 100 - 250 wall units. Lifted streaks have statistically repeatable trajectories.

4) A characteristic mean time between bursts exists. (In later comment W. Tiederman questions data base of this point.) Bursts occupy a low fraction of time but create large fraction of production (70% of average). (Stanford, USC, Gottingen, Ann Arbor)

5) Breakdown is sudden, leads to large region of high spectral frequencies. (Runstadler, Offen; data on this point very sparse).

6) We distinguish "vorticity" in a mathematical sense particularly as present in shear layers from a "revolving vortex", which is observed to make at least one revolution about a recognizable axis. Using this distinction, we note that ω_x vorticity exists but appears relatively low

in the zone $0<y^+\leq 7$-10; and does not appear to be a revolving vortex (this data could be biased by fact that observation can only be made where there is marker). In the zone 7-10$<y^+<$30-50, stronger streamwise vortical motions appear to be present (Kim, Brodkey, Blackwelder).

7) Breakdown is relatively sudden compared to other events in the wall region and results in a large region of both larger and finer scale fluctuations (Offen).

8) The data on ejections reported by Brodkey and co-workers at OSU appear to differ from those reported by Kline and co-workers at Stanford on the y^+ of origin. The Stanford group indicates that the origin is in the low speed-streaks that trace back (well upstream) to layers essentially at the wall, i.e., below $y^+ = 3$. Early OSU work (Corino and Brodkey) reported ejections originating as close as $y^+ \sim 2.5$. However,the more recent OSU work (Nychas, Hershey and Brodkey; Praturi and Brodkey) report ejections from y^+ = 30-40. In discussion, Brodkey indicated that the latter method used at OSU did not make the layers closer to the wall visible; ejections were merely reported where they were seen. Since the Stanford method does allow tracing from the wall (particularly in wall-slot dye injection), there is no real inconsistency. The Stanford model is apparently not subject to contradictory observations, since it shows the motions at y^+ = 30-40 that the OSU group reported, but also indicates their far-upstream origins.

B) Wall Layers: Questions

1) What events (or stages cited above) contributed significantly to $\overline{uv}$?

2) What is significance of "pockets" reported by Falco, Smith?

3) What causes streak lifting?

4) How is the average time between bursts observed in visual data related to time periods from signal detection techniques using probes?

C) Outer Layers: Statements

1) "Bulges" of scale δ exist, contain momentum deficient fluid (Head, Fiedler, Falco, Blackwelder, Kovasznay, Laufer).

2) Zones of irrotational or nearly irrotational high-speed flow occurs between bulges; these have strong wallward motions (often called sweeps).

3) Sharp accelerations occur across the back (upstream face) of bulges (Blackwelder, Falco, Hedley & Keffer).

4) Compact vortical eddies (herein called Falco eddies) exist, the scale of the core of these eddies is $\simeq$ 100 wall layer units. They carry high $\langle uv \rangle$. (These Falco eddies tend to appear along the back of bulges.)

D. Outer Layer: Questions

1) Do other observers agree with Falco that high $\overline{uv}$ is not associated with motions of scale δ (at least at Reynolds

numbers O(1000)) but rather with motions of scale of the order of 100 wall layer units?

2) How are Falco eddies formed?

3) Do Falco eddies relate to the bursting process in the wall layers; if so, how? (Kline).

4) What is the pattern of flow near the back (upstream wall) of bulges near the wall as seen in a convected frame moving with bulge? Sketchy data provided by Falco 1977. (Is flow 2 or 3 dimensional? Does a stagnation point flow pattern exist?).

5) What causes a sweep?

6) What fraction of total uv or production is produced in specific observed structures in the outer layer?

E) Interactions: Statements

1. Inner and outer layers interact (available data eliminate hypothesis asserting either inner dominated or outer dominated, Kline, Lehigh paper).

2) Time between bursts is equal to bulge passage time within the 2:1 uncertainty of the bulk of data.

3) Disturbances exist that propagate at speeds somewhat different from mean speed in both inner and outer layers. These can be viewed as either an eddy or a propagating wave.

4) High $\overline{uv}$ motions in outer layer scale on inner variables (Falco, Head & Bandyopadhyay).

5) Sharp shear layers play a roll in producing high $\overline{uv}$, but see questions below.

F) Interactions: <u>Questions</u>

1. What is the sequence of events that creates high $\overline{uv}$? (Stanford; ejection, breakdown, ejection: OSU; shear layer, vortex, shear layer: Falco; outer Falco eddies create pockets & high $\overline{uv}$ at pocket. Also USC/OSU: suggests shear layers arise on the front between sweep and burst).

2) How do sweeps affect inner profile, bursts?

G) Comments.

1) All observable structural features in boundary layers have high variances.

No summary of theories is presented. This is left for fuller treatment at a later meeting.

Summary of 1979 MSU Workshop

on Boundary Layer Structures

These comments continue the work of July 1978 Stanford meeting.

B. Critical Questions

A list of critical questions submitted by various workers for possible discussion during meeting is attached as Appendix 1979A

C. A review of available data on time between bursts (Tiederman) showed that:

1) Omitting runs by Donohue and Tiederman method II*, the visual data and the high $\overline{uv}$ conditioned quadrant analysis gives consistent results. Probe data conditioned in other ways thus far do not give consistent results. (See also Offen & Kline).

2) The totality of data is <u>not</u> persuasive regarding whether the time between bursts should be scaled on inner or outer variables. (Suggestion: Hanratty could make accurate measurements in tube at high R at wall, will consider).

3) In visual counting it is important to observe sufficiently far downstream from the dye injection slot ($x^+ = 4800$ for non-drag reducing flows).

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*A correction for this method was suggested and will be checked.

4) Work at Urbana (Hanratty) provides a number of measurements at the wall which can be used to augment other data effectively. These data also provide boundary value information for numerical simulations. A review of the history, outlook, status and plans of the work at Urbana was presented by T. Hanratty and is summarized in Appendix 1979B.

Urbana measurements confirm wall streak structure ($\lambda^+ = 100$) by independent wall probe technique.

Current measurements attempt to tie wall probe observations to flow pattern above the wall and should add to understanding of relationships in the wall layers.

5) A summary of six known structural features was presented by Falco (see Appendix 1979C).

Several workers (Falco, Brodkey, Kline) emphasized the need to determine those features that are significant in that they contribute to high $\overline{uv}$, from those that are not. This is an advance from earlier attempts to hypothesize a single simple structural basis, and in both the inner and outer region interpret observations and measurements so as to fit them.

6) In the outer region, new 4-wire data (Falco) shows bulges do not have high uv or high ω_z over most of their extent. Falco eddies do have high $\overline{uv}$. Falco eddies

also have high ω_z with roughly equal contributions from $\partial u/\partial y$ and $\partial v/\partial x$. ω_z peaks under the core of the Falco eddy, but s_{xy} (the strain rate) peaks at the upstream boundary of the eddy. Comment (Kline, Landahl), we need an integral measure of contribution to $\overline{uv}$ in some form such as:

$$R_{uv} = \frac{\int_{y_1}^{\delta} \langle uv \rangle_{\substack{\text{typical}\\ \text{eddy}}} dy}{\int_{y_1}^{\delta} \overline{uv}\, dy}$$

or

$$F_p = \frac{\int_{y_1}^{\delta} \langle uv \rangle_{\substack{\text{typical}\\ \text{eddy}}} \frac{\partial u}{\partial y} dy}{\int_{y_1}^{\delta} \overline{uv}\, \frac{d\overline{U}}{dy} dy}$$

where y_1 equals an arbitrarily determined inner level.
Comment: Form and interpretation of F_p needs discussion.

7) Orthogonal light sheets suggest that Falco eddies are not elongated (hairpin like) structures but are compact. (This is an apparent point of disagreement with current work of Head and Bandyopadhyay).

8) Simultaneous visual and hot-wire data (Falco) show;

a) Sharp shear layers ($\partial u/\partial y$) in the inner layers, their thickness is approximately 50 wall units.

b) High <uv> associated with "pocket" events. (See again comment 6 above.) Highest observed ω_z occurs when pocket intersects lifted low-speed streak (about 3 times mean).

c) Suggests some regions of high uv will not be detected by VITA type detection. However, VITA detection will apparently detect interaction between lifted low-speed streak and a pocket.

9) ω_z in wall layers is primarily $\partial u/\partial y$ (Falco, Brodkey).

10) Report (Falco) that pocket formation is associated with smoke-filled Falco eddies.

11) Report (Willmarth) that hot-wires, even the smallest available, give errors of a factor of 2 (low) for fluctuations at high frequencies. Comment (Kline) despite this calibration of $(uv)_{rms}$ measurements check a primary standard (momentum theorem in channel flow) to 1.25% which is consistent with the accuracy of the standard in low-speed air flow. Suggests that energy in such flows is predominantly below frequencies of difficulty in hot-wire use, and hence that not all hot-wire data are invalidated.

However, the uv effect of sharp-shear layers in boundary layers may be missed by x-wires because of problems of spatial resolution.

12) Because a stagnation point exists, in convected view on a Falco eddy, (Falco, differences will occur in scale measurements between markers introduced in vortical zones and those introduced into outer irrotational flow.

13) Pockets are seen far more clearly in Falco smoke technique and H_2 bubble time-lines than with dye slot.

14) Smith presented H_2 bubble visualization showing strong ejections associated with pockets (confirming Falco's observation - see Lehigh symposium) but giving further details.

15) Several workers indicated that importance of using high $\overline{uv}$ as a discriminator to locate significant structures (events).

16) A similarity appears to exist in breakdown or Taylor-Gortler vortices, see Bippes & Gortler, with pictures of streak breakdown as observed in smoke, light-sheet technique. (Kline, Landahl) comment that other such similarities exist; caution needed.

17) Pressure gradient has an important effect on time between bursts (Schraub & Kline, Simpson). More structure studied for flows other than on a flat plate are needed.

18) ω_x measurements made with Kovasznay type probe are always in serious error (Willmarth). Correct measurements will require 4-wire probes each independently operated.

19) Calculations showing that boundary layers ultimately "erupt" behind a convecting vortex were presented (Walker). See Appendix 1979D for further details.

20) Using the results of inviscid, linearized, stability theory Landahl reported a number of significant suggestions:

a) All inviscid shear flows are unstable to local disturbances;

b) Local "v" fluctuations give time-wise growth of high and low-speed u;

c) This concept produces a prediction of how u is related to instantaneous profiles conditionally sampled to the bursting period;

d) stretching of spanwise vorticity is necessary to this theory;

e) in this theory times exist in which ω_z of sign opposite to mean spanwise vorticity are created.

21) Hanratty presented a remarkably simple theory which reproduces a number of known wall-layer features. It assumed homogeneity in the x direction and uses a spanwise periodic boundary condition at $y^+ = 46$ in which the streak spacing ($\lambda^+ = 100$) is used for the spatial period. The calculation is temporarily periodic and uses the experimentally determined time between bursts to set the period.

22) Moin and Kim presented a large eddy simulation of a fully established channel flow in a 64 x 64 x 64 grid recently completed on ILIAC.

a) Many known wall layer features are reproduced and some new features for which measurements are lacking are simulated.

b) Long high/low velocity streaks in streamwise direction appear in wall layers, but long zones of ω_x are <u>not</u> found.

c) ω_x is found to be a maximum at $y = 0$ contradicting the one set of known data (can use Hanratty data to check magnitude).

d) Pressure-strain correlations are found to be significant relative to the terms in the turbulent kinetic energy equation particularly at $y^+ \leq 10$.

The correlation of $\overline{uv}$ decays at very long computational times suggesting that a wholly dissipative subgrid closure model may not be appropriate -- that is, some feedback of energy from smaller scales may be necessary to simulate the physics.

In agreement with OSU data, primary contributions to $\overline{uv}$ near wall come from sweeps, but farther ($y^+ = 100$) from wall come from ejections.

(Suggestion: Moin-Kim study details of events in zones of time and space where high $\overline{uv}$ occurs to augment experiments).

(Question: can the Walker-Abbott theory be used to assist in the resolution of scales near the wall in simulation.) ω_x near wall consists almost wholly of $\partial w/\partial y$. Sign of ω_x found contradicts some theoretical models.

23) Regarding the comment (Bradshaw at Lehigh and in letter to MSU workshop) that scales of structures in the log zone must be proportional to distance from wall, there was agreement that this need only apply to shear producing structures and only on the average.

24) Further discussion of what quantities define instantaneous turbulence production is needed. The difficulty raised by Brodkey et al (Phys. Fluid <u>16</u>, 2010 (1973) is that the instantaneous uv does not work against the average strain rate $\partial\bar{u}/\partial y$, and detailed measurements need to take this into account. Agreement on method does not yet exist.

Appendix 1978 A

DEFINITIONS

I. Lagrangian Terminology

A. Streak: A high- or low-speed (relative to the mean) region in the linear sublayer, highly extended (aspect ratio greater than 10:1) in the flow direction.

B. Low-Speed Streak Lifting: Outward movement of fluid in the low-speed streak to a point outside the linear sublayer.

C. Linear Sublayer: y^+ less than 7-10.

D. Streak Oscillation: Apparent amplifying three-dimensional oscillation in side and plan view of a lifted low-speed streak.

E. Wall Scales: ν/u_τ, u_τ.

F. Mixing Region: Region after a breakdown in which chaotic motions affect a large propagating region.

G. Breakdown: An abrupt event in which the streak oscillations terminate in the formation of a large region containing a wide range of small scales.

H. Bursting: The set of processes beginning with the lifting of low-speed streaks and terminating at the end of the mixing region.

I. Quiescent Period: Period between bursting processes.

J. Visual Ejection (after Brodkey & Corino): Rapid motion away from the wall of fluid that came from a decelerated region and penetrates into the log region. NOTE: The Stanford group uses "ejection" to denote motion from linear sublayer into the outer layers.

K. Visual Sweep (after Brodkey & Corino): Large-scale inward motion of faster moving fluid, producing local acceleration in the flow field.

L. Log Region: y^+ greater than 30-40 but less than wake matching point.

M. Compact Vortical Flow Structure: A compact, coherent, three-dimensional, ring-like structure observed in the outer region of the turbulent boundary layer having a characteristic core diameter of about $L^+ \sim 100$. NOTE: This is called "typical eddy" by Falco, but the name seemed to lack specificity for several attendants.

N. <u>Bulge</u>: A large-scale, three-dimensional structure which dominates the visual appearance of the outer layer, with scales of the order of the boundary layer thickness.

O. <u>Valley</u>: Region between bulges in which outer fluid penetrates the (average) boundary layer thickness.

II. <u>Eulerian Terminology</u>

A. <u>Scale</u>: Characteristic dimension of a recognizable flow structure.

B. <u>Coherent Structure</u>: A confined region in space and time in which definite phase relationships exist among flow variables.

Appendix 1978B

SCALES

The following is the result of discussion on interpretation of the usually undefined terms small, medium, and large scales.

In a turbulent boundary layer, we can use the following associations:

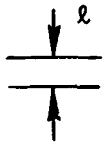
Scale Size	Math Expression	Other Names
Large	δ (or size of apparatus, whichever is smaller)	Integral scale
Medium	$50 < \ell u_\tau/\nu < 300$	$\sim$ Taylor Microscale
Small	$1 < \ell u_\tau/\nu < 10$	Kolmogorov Scale

(<u>Note</u>: Motion of scale $\ell u_\tau/\nu < 1$ dies rapidly, owing to viscosity.)

ℓ = characteristic size of coherent motion, $u_\tau = \tau_w/\rho$.

Using these scales, we agreed that a criterion for a "sharp shear layer" can be taken as:

Width of layer



$$\frac{u_\tau^2 \ell}{U_\infty \nu} < 0.5$$

Or, since

$$\frac{u_\tau^2 \ell}{U_\infty \nu} = \underbrace{\frac{u_\tau}{U_\infty}}_{\sqrt{C_f/2}} \cdot \underbrace{\frac{u_\tau \ell}{\nu}}$$

$$\text{order} \quad 0.05 \cdot 10 = 0.5$$

This gives the result that the thickness of "sharp shear layers" is of order of the linear sublayer thickness, regardless of where the layers occur.

Appendix 1979A

QUESTIONS ABOUT TURBULENT BOUNDARY LAYER STRUCTURE

I: General

1. How many coherent motions, each of which is identified by a well defined physical process, must be considered?

2. Which of these coherent motions contribute significant uv? Which contribute a significant fraction to $\overline{uv}$?

3. Which are responsible for the generation of sharp shear layers (which, via instability, are responsible for a redistribution of vorticity)?

4. Which, if any, are responsible for high strain-rate and dissipation?

5. How many interactions between these coherent motions need to be considered for a first order picture?

6. How does the term which defines the production of turbulence in the turbulent energy equation relate to the local instantaneous transfer of energy which accompanies coherent structure movements and interactions? What is an appropriate measure of instantaneous turbulence production?

7. What aspects of the heuristic models are likely to be affected by the addition of a dilute concentration of a long chain polymer?

II. Inner Region

1. Can a property of the bursting process be agreed upon which can be uniquely detected by point measurements?

2. What features of wall layer structure and evolutions are governed by wall layer parameters?

3. What causes the lift-up of sublayer fluid?

4. Does the lifted fluid oscillate, or is it pushed from side to side by ambient motions?

5. Is breakup an event distinct from the gradually growing loss of coherence of the lifted waving marked fluid?

6. What phase of the bursting sequence results in the highest uv?

7. Why is $\lambda^+ \simeq 100$?

8. How does the time between bursts scale?

9. How do streamwise vortices form, and how are they related to the less frequently observed transverse vortices? What is the extent of these vortices?

10. Is this streamwise vorticity a cause or result of the bursting process?

11. Is the Walker mechanism, in which a single vortex tube interacts with the wall to produce lift-up, important in the inner region?

12. How does the evolution of the pocket flow module relate to the bursting sequence of the Stanford studies?

13. How does the wall region sequence associated with ejections, as described by Corino and Brodkey, relate to the sequence described by the Stanford studies?

14. Is the creation of local sharp shear layers (instantaneous inflected velocity profiles) important in the inner region? What role do they play in the Stanford burst sequence and/or the Corino and

Brodkey sequence? Why is the wall region flow apparently stable with respect to high $\partial u/\partial z$ as noted by Corino and Brodkey (their "two layer" effect)?

15. Are the "fingers" of high speed fluid noted by Praturi and Brodkey related to the high speed streaks of the Stanford studies?

16. Do sweeps come before lift-up (or ejection) as indicated by Offen and Kline or vice versa, as indicated by Corino and Brodkey?

17. Does the streak spacing non-dimensionalized by u_τ and ν remain constant at high Reynolds numbers?

III. <u>Outer Region</u>

1. What percentage of the Reynolds stress is associated with the Reynolds number dependent Falco eddies?

2. How do Falco eddies form, evolve and decay?

3. What is the relationship between Falco eddies and the bulges or large scale motions of the outer region?

4. Why do Falco eddies, which are regions of high uv, high Ω, and high strain rate, scale on wall region variables?

5. What is the relative importance of elongated loops emphasized by Head and Bandyopadhyay to the compact Falco eddies? Are the loops the diffused remnants of the marker that initially concentrated in a Falco eddy?

6. Are the transverse vortices seen by Brodkey's group, and the Falco eddies, the same coherent motion?

7. Can Falco eddies be important at high Reynolds numbers, where the Reynolds number independent law of the wake holds?

8. Are the large scale motions of the outer region best described as three-dimensional regions of velocity defect which cause higher speed fluid to move around them, resulting in the formation of a convected stagnation point flow somewhere along their upstream boundary (Falco 1977) or as large scale transverse vortices?

9. What is the effect of Reynolds number on the large scale structure?

10. Are sweeps the result of wallward motion due to the stagnation point flow noted above (pressure forces), or a result of large scale transverse vortices?

11. Is the answer to question 10 the major part of the answer to the entrainment question?

IV. Inner-Outer Interactions

1. What is the relative importance of the following interaction mechanisms?
   (a) The passage of large scale motions of the outer region impose conditions on the wall. Do these conditions produce the observed wall layer structure which then goes unstable (various proposals have been made by Coles, Laufer, Townsend, Willmarth)?
   (b) Fluid regions, observed to move towards the wall, appear to be associated with the disturbance of existing wall layer structure, which results in the bursting sequence. What is the nature of this interaction, i.e., is it just the result of satisfying continuity (Brodkey), is it the formation and consequent instability of a shear layer (Blackwelder), is it vortex induction (Nychas et. al), is it the vortex/wall (viscous governed) instability mechanism (Falco, Walker), or is it the formation of local convected separated regions which then lift-up as a result of vortex roll-up or pairing (Offen and Kline).

2. Are outer layer vortices, either Falco eddies or Brodkey's transverse vortices, directly associated with the lift-up of sublayer fluid by vortex induction?

3. Can the lift-up or ejection of sublayer fluid be phased to large scale bulges of the outer region?

4. Must we explicitly consider three-dimensional motions (for example, vortex stretching) to explain the inner-outer interaction?

5. Are the sweeps, which produce high uv in the wall region and cause the formation of pockets, directly associated with the large scale outer region sweeps? Are these sweeps, or the larger scale sweeps which can't produce high uv in the wall region, associated with the bursting sequence?

6. Is the cycle of wall region events suggested by Offen and Kline, independent of the large scale outer region motion?

7. What is the relationship between the fingers of high speed fluid (seen by Praturi and Brodkey), which are associated with ejections, and the large scale outer layer motions?

8. Why is the wall region velocity scale, u_τ, important in the outer region (for example it scales turbulence intensity, Reynolds stress, all equilibrium boundary layer scaling, Falco eddies, etc). How does this information get carried to the outer region?

9. How do the large scale motions of the outer region form?

Appendix 1979 B

Beginning

A. Hanratty - 1956 — Use of surface renewal model to describe flow close to wall

Ph D Theses

B. Reiss - 1962

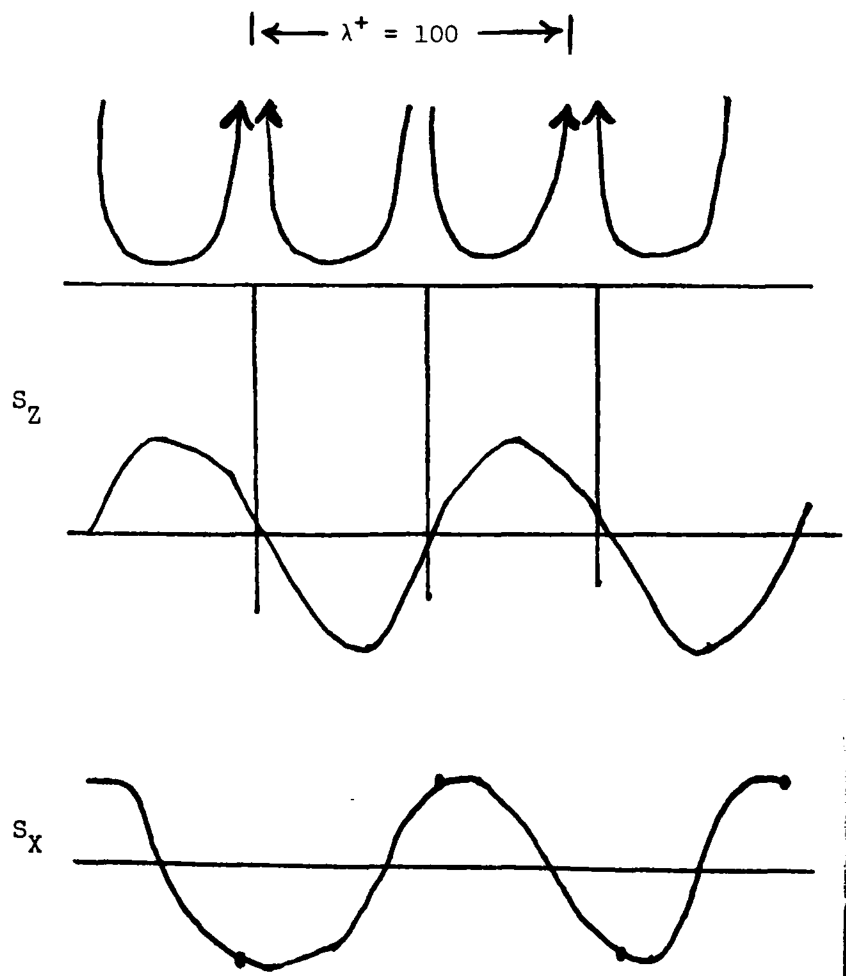
1. Invented electrochemical technique
2. Discovered existence of elongated flow structures close to wall. (In agreement with the 1963 report of Runstadler & Klein)

C. Mitchell - 1965

1. $(\overline{s_x^2}) / \bar{S}_x = 0.32$
2. $L_x/L_Z \cong 30$

D. Sirkar - 1969

1. Invented technique for measuring s_z –
2. $s_z/s_x \cong 0.3$
3. Suggested regular eddy model



Elongated symmetrical eddies (intensity of inflow and outflow about the same intensity) control the transport of heat, mass and momentum--
Similar to Bakewell (1966 thesis) proposal--and to previous proposal by Townsend--but differs in that does not assume gradual inflow and jetlike outflow and in that it assumes these eddies control the transfer to the wall; That is, Sirkar proposed a mechanism for the creation of momentum deficient fluid.

4. Confirmed the suggestion of Bakewell (1966) that the frequency of velocity fluctuations in the viscous wall region scales with wall parameters (thus changing our previous notions expressed at the Kyoto Meeting of IUTAAM)

E. Eckelman - 1971

1. Developed method for measuring s_x and s_z at multiple locations
2. Confirmed Sirkar's suggestion of sinusoidally shaped s_z-pattern of wave length $\lambda^+ \cong 100$.

F. Fortuna - 1971

Made a pseudosteady state assumption.
Used Sirkar's model to predict $\overline{U}(y)$ and $\overline{u^2}(y)$.

G. Lee - 1975

Showed the phase relation between s_x and s_z suggested by the Sirkar model

H. Hatziavramidis 1978

Did not use a pseudosteady state assumption.
Used a regular eddy model with wave length $\lambda^+ = 100$ and period equal to that of bursting.

I. Hogenes - 1979

1. Use multiple wall probes and multiple probes in fluid to study structure.
2. Support of the Sirkar model
3. Use of multiple wall probes to determine s_z-patterns for conditional sampling.

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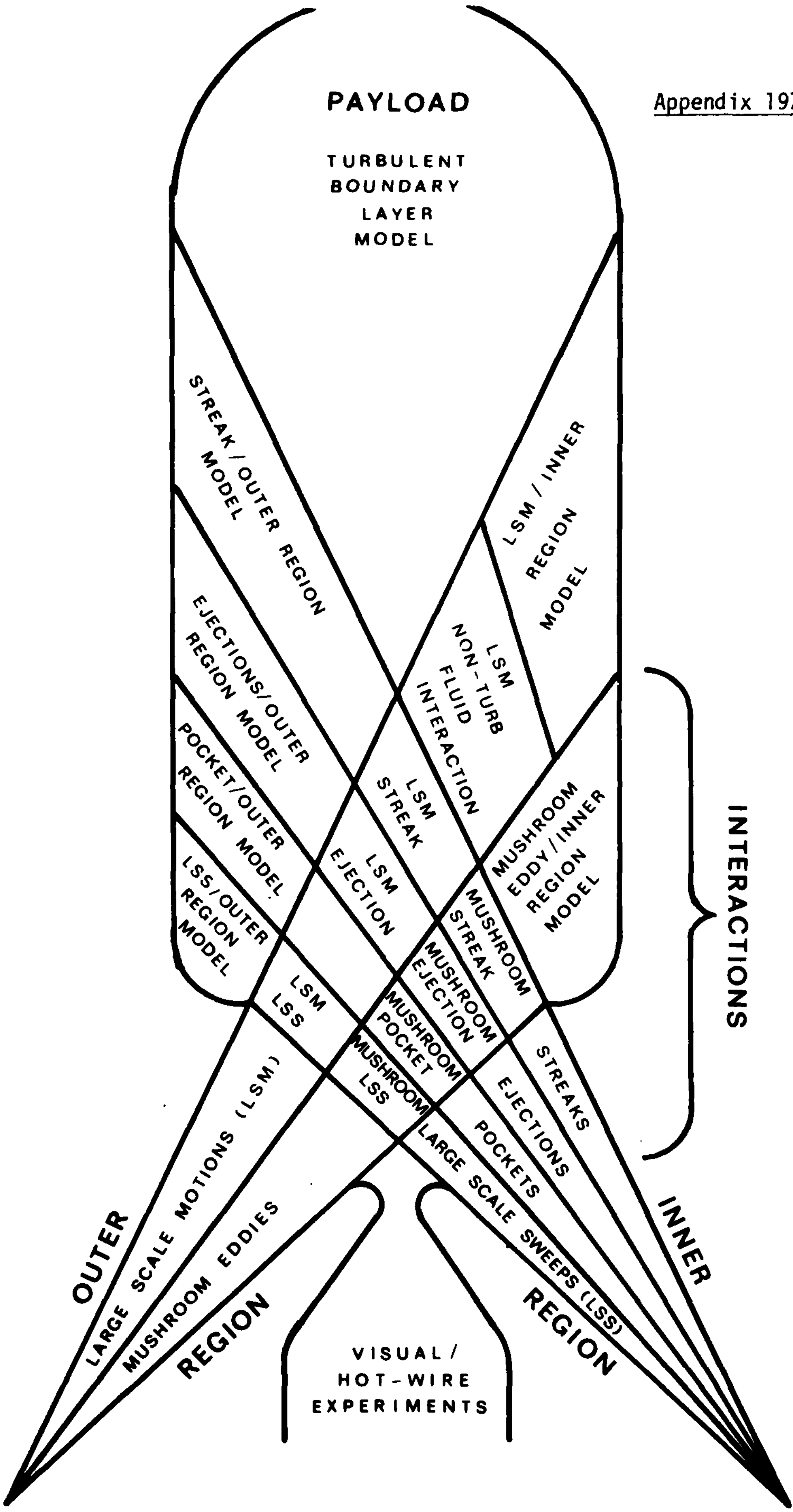
Appendix 1979 C



Structure in the inner and outer regions and possible structure-structure interactions.

Appendix 1979 D

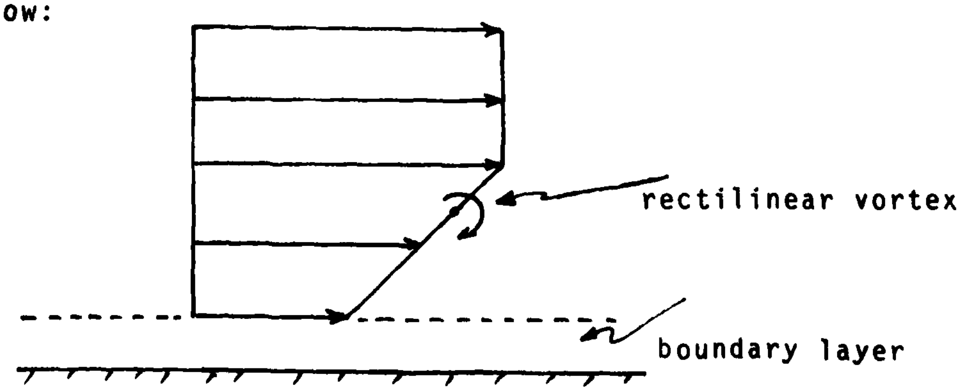
Theory - Dave Walker

1. Numerical solutions for the unsteady laminar boundary-layer flow induced by a rectilinear streamwise vortex convecting in a uniform flow above a plane wall were reviewed. These studies were of a fundamental nature and were undertaken as a search for a possible physical mechanism for bursting in a turbulent boundary layer. The numerical solutions strongly suggest that the boundary layer will ultimately erupt behind the convecting vortex for all convection speeds. This localized breakdown of the boundary-layer flow is expected to occur relatively rapidly and is characterized by a strong upwelling behind the convecting vortex.

2. It was conjectured that the increasingly severe thickening of the boundary layer behind the vortex eventually leads to a viscous-inviscid interaction with the outer inviscid flow; moreover it was speculated that in this interaction another vortex would be created in the following way. As the erupting fluid from the boundary layer penetrates into a region of crossflow above the wall, a roll up phenomenon into another vortex could then occur. This physical process thus gives a possible explanation for the regeneration of vortex structures in a turbulent boundary layer.

3. As yet, the numerical calculations cannot be carried out to the point where the interaction with the outer flow occurs. However, Chuck Smith presented some experiments supporting the proposed nature of the interaction; in these experiments a two-dimensional vortex was created and the effect of the vortex as it passed over a flat plate was observed. The flow visualization was carried out in a convected reference frame using hydrogen bubble wires. An upwelling from the boundary layer on the plate was observed which became more pronounced as time increased; eventually a rollup into another vortex structure was observed.

4. The calculations presented were for the case of a rectilinear vortex for which the vorticity is concentrated. However, it was mentioned that other situations of two-dimensional vortex motion in which the vorticity is distributed over a finite area had also been considered; in these cases, the conclusions were essentially the same as for the rectilinear vortex case. In addition, preliminary calculations were mentioned for the case of a vortex embedded in a shear flow as below:



The parameters in the polygonal profile were selected to model the mean profile for the Andersen et al (1972) zero pressure gradient data in the outer region of the turbulent boundary layer. In a frame of reference convecting with the vortex, the boundary layer ultimately thickens severely in the region of adverse pressure gradient behind the vortex.

5. The calculations imply that a laminar boundary layer cannot withstand the motion of a two-dimensional vortex above it without ultimately erupting. For a three-dimensional loop filament of vorticity which are present in the outer layer of a turbulent boundary layer, vortex stretching will play an important role in the dynamics of the loop. However, it appears likely that at least a laminar boundary layer will erupt in response to the motion of a three-dimensional vorticity loop above it; the nature of the eruption is probably more complicated than in two dimensions but it seems hardly unlikely that the effect of vortex stretching can negate the basic effect. This notion was supported by some preliminary experiments reported by Bob Falco in which a single vortex ring passing near a plane wall evidently caused an abrupt and violent ejection of fluid from the boundary layer near the wall; it was pointed out by Falco that the effect he observed could not be explained on the basis of inviscid theory.

Further support for this type of mechanism was mentioned by Chuck Smith (1978) in connection with his flow visualization studies in a fully developed turbulent boundary layer; these experiments were carried out in a convected reference frame using a hydrogen bubble wire. In this technique,the bubbles make visible the flow in a plane through a three-dimensional vortex structure. It was noted that eruptions seem to occur behind the head of the moving vortex structure; these eruptions occur from the wall layer, resemble Corino and Brodkey's (1969) fingers of fluid and ultimately are observed to crest and roll up into another vortex structure.

6. A vital feature of the proposed mechanism is that viscosity is an important feature in triggering the eruption of the boundary layer although the interaction with the outer flow is probably inviscid in character. An analogy in connection with transitory stall in diffusers was mentioned by Steve Kline; in this situation, viscous separation in the boundary layers ultimately gives rise to a large scale inviscid interaction in the diffuser. However, the viscosity is a vital feature of the phenomenon in initiating the interaction.

   In connection with the turbulent boundary layer, the proposed mechanism is that it is the rotational flow in the outer layer which gives rise to a separation

effect in the wall layer and which ultimately results in an interaction with the outer layer.

7. This idea of the importance of viscosity in the bursting process appears to be supported by the large scale eddy simulations of channel flows carried out by Moin, *Reynolds and Ferziger (1978). In these calculations,* the viscous terms in the Navier-Stokes equations are retained and the no slip condition is applied at the channel walls. The proposed mechanism is in apparent contradiction to the mechanism proposed by M. Landahl who regards the bursting process as a primarily inviscid phenomenon. It was suggested that it might be interesting for P. Moin to remove the viscous terms from his program, apply only the solid wall condition in his channel flow calculations and see how these calculations compare with those where viscosity is included.

Appendix 1979 E

A review of the current state of knowledge of turbulent boundary layer structure.

by

R. E. Falco

The discussions of experimental information could be divided into three parts; outer region flow structure, wall region flow structure, and interactions between the outer and wall region. The largest body of information is associated with the wall region, although it was made clear that important aspects are still being uncovered. Knowledge of the outer region is growing rapidly. Very little is known about the nature of interactions between the outer and wall region beyond the fact that such interactions do take place.

Theoretical discussions centered around the wave focusing mechanism of Landau, and the vortex wall instability calculations of Walker. Discussion about the results of large eddy simulations, where they might help and be helped, followed. It is my purpose in this summary to relate factual information discussed at Stanford, but more importantly to present it in an expanded framework about which future discussions may revolve.

The wall region

It is not my intent to review the current state of knowledge of wall region structure as this was admirably done by Kline (1978) and Willmarth (1978, 1975). At the meeting, attention was focused upon the degree of confidence that could be assigned to various experimental findings which were associated with the picture of the wall layer bursting detailed by Kline (1978). It was agreed that when only the wall layers are marked, a marker can be seen to lift up, oscillate and breakup. Details such as the constancy of the wavelength of oscillations, why the oscillations are three-dimensional, and

whether they grow in time as they are convected downstream were left open. Considerable interest was expressed in the rapidity of the breakup which was divided into a breakdown region followed by a mixing region. Limited evidence suggested the spectrum during breakdown has more energy at both small and large scales. Both visual and hot-wire information argue that breakdown is accompanied by creation of both smaller and larger scales. This process was not understood. The uv content in the breakdown and mixing regions was high, but it was low in the oscillatory stage. More evidence on the uv distribution over the bursting process would be useful. Kline noted that the streaks do not have much streamwise vorticity until they lift up. This was confirmed by measurements of Blackwelder (1978) made in the linear sublayer. Hence the motions contain ω_x but are better thought of as upwellings and downward motions than "revolving vortical structures." This was agreed upon at the Stanford meeting. Participants further agreed that a zone existed above the linear sublayer where strong vortical motions (revolving vortices) exist ($10<y^+<30-50$). The peak in rmsω_x occurs at $y^+ \approx 20$, Willmarth (1977).

Looking at the wall region structure as it appears in planes parallel to the wall, a new element emerged. Falco (1977b, 1978a,b) indicated that there appeared to be a double structure in the wall layers. The long streaky structure documented by the Stanford studies, and a shorter flow module which appears as a pair of short streaks emanating from an upstream apex (see Figure 1). These flow modules are called "pockets". The pockets have a non-dimensional spanwise width of $z^+=90$ and a length about 30% greater. They appeared to be footprints of important components of the large scale sweeps. The pockets, in general, evolved more rapidly than the longer streaks. Smith (1978b) showed results using a convected hydrogen bubble wire that confirmed the existence of the pockets. Later work by Falco (1978b) showed that the uv contributions from pockets were the highest contributions found at $y^+ = 16$. At the Lehigh conference Falco (1978a) showed that fluid was

ejected from pockets after they formed. Smith (1978b) also showed ejected fluid emanating from pockets. Furthermore, Falco showed that the pocket/ejection sequence did not depend upon the existence of the long streaky structure. Pockets formed both in between long streaks and right on them.

The laser sheet visualization (Falco 1978b) also shows the long streak evolution very clearly; in particular, the wavy growth and the breakdown of the oscillations. Details of the breakdown look very similar to the wavy growth and breakdown of a low Reynolds number wake (see Figure 1 and pictures of Holman in Schlichting "Boundary Layer Theory"). Once oscillations begin to appear in a long streak, the time to breakdown is comparable to the evolution time of the pockets (see Figure 1).

On the whole several important aspects of the wall region structure remained unexplained. For example, why do we get a spacing of $y^+ \simeq 100$ for the long streaks? Why do we get the long streaks? These are many times longer than the streamwise length of large scale motions in the boundary layer. What causes them to oscillate? To lift up? Is the breakdown sequence for the pocket flow module different from that of the long streaks? Is it the same? What is the relative importance of these two structures? Falco suggested that Kline's bursting sequence qualitatively resembled the sequence of events that dye placed on a wall undergoes when a vortex ring impinges the wall at a shallow angle (see discussion on inner-outer layer interactions). What is the correspondence between the bursting sequence outlined by Kline and the sequence discussed by Corino and Brodkey? Because their description is in terms of accelerations and decelerations rather than in terms of velocities it is difficult to see where it fits in. (Brodkey's attendence (Summer 79) may resolve this question). Finally, it was agreed that the stages of the bursting sequence have, so far, not been uniquely connected with specific signal characteristics obtainable with hot-wires or LDV (note, Offen and Kline have obtained ensemble averaged signatures of u,v, uv

along a line through the sequence).

The existence of two different flow modules in the wall layers seriously complicates attempts to match hot-wire signals to visual impressions. Since interpretation of hot-wire information has hinged upon a physical picture derived from visual information, it is essential to get the visual picture correct. But it is possible that the predisposition of investigators to come up with one sequence of events, combined with the limitations of visual techniques has led to a composite picture of two different flow modules on the one hand, and to the current position that the apparently different physical picture of the Ohio State group from the Stanford group is the result of using different flow visualization techniques.

An important purpose of the proposed meeting is to present hypotheses of this sort as "challenge positions" which, if carefully worked through, will by the process Kline (1978) calls negative inference, lead to a firmer foundation for the single flow module concept or dispose of it. It is important that "challenge positions" have what appears to be substantial supportative evidence. I will illustrate by making a brief defense of the position that it is simply a result of the limitations of visual evidence that the double structure was not explicitly identified. It is my opinion that different visualization techniques can emphasize <u>different</u> flow modules. The Stanford dye and hydrogen bubble techniques emphasize the long streaky structure and its evolution, while the particles emphasize the pocket flow modules. For example, wall dye injection can only detect pockets very close to the ejector where it is impossible to tell whether a streak corresponds to the side of a pocket or the downstream end of a long streak. Further away from the injector, the dye primarily collects in the long streaks which have a long lifetime compared to the pockets, thus making it impossible to see pockets which form in between long streaks, and severely hampering the view of pockets which form on, or partially on, the long streaks. The same comments

apply to hydrogen bubble wire visualization with the wire in the laboratory reference frame. In spite of these difficulties, reexamination of visual results of Rundstadler, Kline and Reynolds (1963) clearly show pockets near the wire. However, if the wire in a plane parallel to the wall is convected at a speed close to the convection velocity of the pockets ($\approx .4U_{oo}$) as Smith (1978b) has done, the pockets can be clearly seen. (As noted above another method which clearly shows the pockets as well as the long streaks is volume "smoke" flow visualization (Falco 1978a,b) see Figure 1).

In Falco's (1978) experiments the two flow modules have different origins. Pockets (as will be noted in the section on inner-outer region interaction) result from high speed motions coming towards the wall, whereas the origin of the long streaks and the reason for their growing waviness is not known. It is possible that the short, energetic longitudinal vortices clearly noted by Kim, Kline and Reynolds (1971) and by Brodkey (1978) and Praturi and Brodkey (1978), which are "centered" about $y^+=5$-15 and extend from $y^+\approx 10$ to 25 may be characteristic of the pocket flow module and not of the long streak flow model in its wavy breakdown stage. Brodkey (1978) roughly estimates them to have a length $\ell^+=100$, the order of the pocket length. This is speculative, but there is growing evidence that this strong streamwise vorticity seen above the linear sublayer comes in counterrotating pairs. (Note, I am not referring to the possible existence of long streamwise vortices that may result in the long streaky structure.) This was first noted by Schraub and Kline (1965) and more recently by Smith (1978a,b) and Brodkey (1978). It is unlikely that two long streaks would break down simultaneously or that they would necessarily result in counterrotating vortices. Furthermore, the streamwise vortices undergo a 360° rotation over axial distances much smaller than the measured wavelength of the long streaks during the wavy stage of the long streak bursting process which has wavelengths of $\ell^+\approx 250$ and furthermore, the distance over which these streamwise vortices have been observed is only approximately 100 wall

layer units. Kim, Kline and Reynolds (1968) carefully pointed out that some lift ups had axial vorticity associated with them, and others just evolved into a wavy motion. Corino and Brodkey (1969) carefully looked for indications of oscillations in the wall layer fluid before they observed ejections, but found none! Nine years later, after several reexaminations, Praturi and Brodkey (1978) indicate that axial vortex motions were seen in Corino's movies in the limited field of view (about $y^+=90$, $x^+=125$); however, they could not see the oscillations of the long streaky structure ($\lambda^+ \approx 150-250$).

There is also considerable confusion as to whether the hypothesized long vortex pairs that lead to the long streaks are associated with the short axial vortices mentioned above. In addition to the comments made earlier, measurements of Bakewell and Lumley (1968) also suggest very weak circulation in the y-z plane near the wall. The fact that strong axial vortices are noticed above the linear sublayer leads to questions about the source of ω_x, or questions about the amplification mechanism of existing ω_x. Several possibilities exist, but this is a point about which more data is required. Rotation of ω_z after lift up or amplification of ω_x components found in sweeps are two examples, the latter will be alluded to later.

It is felt that the response to challenge positions like this will result in significant progress.

Outer region

Our knowledge of the outer region has increased significantly in the last ten years. A picture in which large scale motions (the tops of which are the bulges of the outer edge of the boundary layer) extend across a major fraction of the layer was agreed upon by all present. These had been observed by Falco (1974), Chen (1975), and commented upon extensively by Falco (1977a), Head and Bandyopadhyay (1978), and Chen and Blackwelder (1978). Falco (1975, 1977) had observed that the large scale motions did not have a strong rotation in streamwise

planes as suggested by many earlier observers (see for example Blackwelder and Kovasznay 1972). Head and Bandyopadhyay confirmed this. Some disagreement exists about the flow field near the back of a large scale motion. Blackwelder (1978) suggests that it is a strong shear flow whereas Falco (1977a), and Brown and Thomas (1977) suggest that a stagnation point flow (for an observer moving with the eddy) is more appropriate. This has important implications as far as inner-outer region interactions are concerned. All participants agreed that upstream of the large scale motions fluid moves towards the wall. In the stagnation point large scale motion picture, fluid in the lower upstream portion of the large scale motion also moves towards the wall. Falco (1976, 1978b) showed that these large scale motions were highly three-dimensional, and that the variance from the Kovasznay "football" shaped average picture was very large.

Large scale wallward moving flows which extend from the outer edge of the layer to the wall have been observed by Nyches, Hershey and Brodkey (1973), Falco (1974, 1977a), Chen and Blackwelder (1978), and Praturi and Brodkey (1978). Ensemble average values of their strength at $y^+=67$ were given by Falco (1977a). He showed that crevices extended from the outer edge deep into the layer in between bulges which defined the tops of large eddies and that these crevices contained wallward moving high speed fluid (i.e. they are sweeps). However, they are quite narrow in the streamwise dimension in the inner part of the layer. It is likely that these sweeps on average may be composed of fluid which is only weakly vortical, since much of it has come from outside the boundary layer, although they can convect the strongly vortical Typical Eddies, which may be in their path, towards the wall. He further showed that under the downstream side of roughly half of the large scale motions,wallward moving high speed fluid is also found. These sweeps are wider in the streamwise direction, and on average will be more vortical. There is disagreement

over the origin of these large scale sweeps. Falco (1977a) suggested that they arise as a result of the response of fluid outside of the boundary layer to the emergence of a bulge which has streamwise momentum defect. The fluid must go around the bulge. The result is a stagnation point flow pattern (as seen by an observer moving with the bulge) which results in flow towards the wall as well as flow over the bulge and lateral flow. Experiments using two mutually orthogonal sheets of light (Falco, unpublished) indicated that strong lateral velocity components of the sweep are particularly apparent. Praturi and Brodkey (1978), working at very low Reynolds number, suggest that the large scale sweeps are induced by the vortical nature of the Typical Eddies (which they call transverse vortices) found in the outer flow. A major problem with their model is that the scale of the Typical Eddies decreases to a small fraction of the layer (Falco 1974, 1977a) at high Reynolds number. Thus they certainly could not account for the large scale sweeps (which extend across almost the entire width of the layer) at high Reynolds number. Furthermore, the large eddies also don't have significant rotation at high Reynolds number to account for sweeps via an induction effect (see Falco 1974, 1977a, and Head and Bandyopadhyay 1978).

Falco (1977a) showed that the major contribution of uv was not due to the large scale motions, but to an intermediate scale coherent motion which forms on the upstream side of the large scale motions. This was called a "Typical Eddy". This is in strong contradiction to many published results (for example, Blackwelder and Kovasznay 1972 claim that $\simeq$80% of $\overline{uv}$ is associated with the large scale motions). It is true that Falco's results were for $R_\theta \simeq 1000$ and Blackwelder and Kovasznay for $R_\theta \simeq 3000$, and that Typical Eddies decrease in scale as R_θ increases. Thus, so far, hard evidence for this statement only exists for low R_θ layers. (At Stanford it became clear that many participants did not like this name, so it was called a compact vortical flow structure, but I am resorting to "Typical Eddy" for brevity). Typical Eddies have been seen by

Nychas, Hershey and Brodkey (1973), by Brodkey (1978), Praturi and Brodkey (1978), and by Smith (1977, 1978a). These authors also agree that the Typical Eddies form in the outer region, and Smith has confirmed that they form on the backs of large scale motions. Nychas, et al, (1973) and Praturi and Brodkey (1968) see them as forming at the interface between high speed and low speed regions. This interface is of course at the back of a large scale bulge and thus there is agreement on formation location. The mechanism of generation of the Typical Eddies was not resolved. Nychas, et al, (1973) suggest that they form via a Kelvin-Helmholtz mechanism. However, the three-dimensional vortex ring-like nature of these eddies makes this seem improbable. They scale on ν and u_τ, and over a few decades are close in magnitude to the Taylor microscale. The possibility that the Typical Eddies are not vortex ring-like, but instead hairpin-like, was raised by Head and Bandyopadhyay (1978), but experiments by Falco (1977a, also unpublished reports) using two mutually perpendicular sheets of light to examine the Typical Eddy shape clearly dismissed their conjecture in the turbulent boundary layer (in spots, hairpins can be observed at the upstream boundary). Brodkey (1978) also noted that they never saw horseshoe vortices.

On the whole the outer flow structure appears to be reasonably well understood at low Reynolds numbers. Certainly more details are needed, especially with regard to three-dimensional evolution and creation of events, but no new aspects arose. A picture similar to that discussed by Falco (1977a) received general agreement.

Inner-outer region interactions

Agreement that outer flow fields play an important part in the turbulent production process was unanimous. This fact was clearly shown by Wallace, Eckelmann and Brodkey (1972) and Grass (1971) when they measured the contribution of the Reynolds stress due to fluid moving towards the wall. Disagreement exists over the origin, extent and nature of the sweeps

found near the wall. Most participants agreed that there was a connection between the sweep events and the bursting sequence. The problem of inner-outer region interaction is the focus of much current research in turbulent boundary layers, and was clearly the central topic of the meeting.

Although sweeps directly contribute to the production of turbulence near a wall because they contribute to $\overline{uv}$, attention has focused upon them because of their possible role in the bursting process. Nychas, et al, (1973), Eckelmann, Nychas, Brodkey and Wallace (1977), Blackwelder (1978), Brodkey (1978) and Praturi and Brodkey (1978) all propose that the ejection of sublayer fluid is directly connected to pressure effects brought about by the interaction of the large scale sweep with the wall. Nychas, et al, in a visual investigation, suggested that transverse vortices found in the outer region, which are slices through the Typical Eddies observed by Falco, induce ejections by the pressure field they set up on the wall. Eckelmann, et al, showed that pattern recognized signals were consistent with a visual picture suggesting that the incoming sweep "pushes" wall layer fluid up. Their quadrant breakdown shows that the sweep has the highest transverse vorticity associated with it of any of the other motions. A criticism that can be made is that there is no reason to expect the fluid to go upward rather than spread laterally, especially since they say the sweeps should be pictured as "finger-like" motions. Furthermore, if fluid were found to move up off the wall, the scale of the ejected fluid should be comparable to that of the sweep. This contradicts the results of Corino and Brodkey (1969). They found that ejections which occurred while the fluid was being accelerated were of small scale, approximately 5-20 wall layer length scales. Blackwelder (1978) proposes that large scale sweeps will cause a lifted wall layer streak to oscillate and breakdown. He suggests that the high-speed fluid riding over the lifted low speed sweep will lead to a "free" shear layer type instability at the boundary. Furthermore the sweeps are thought to lift the streaks via a

pressure effect, thus this aspect of the model is amenable to the same criticism mentioned above. Blackwelder has only hot-wire information, and therefore is inferring that this picture is consistent with his signals, he is not observing these events directly. Brodkey (1978), and Praturi and Brodkey (1978) in visual investigations suggest that a high-speed sweep resembles a hand. The wall layer fluid which is trapped between the fingers of the hand is forced to move away from the wall as a consequence of continuity. They see the longitudinal vortices on the wall region as being produced by the transverse gradients in streamwise velocity which exist at the boundaries of the fingers. Although they had a three-dimensional view, it is hard to see how a roughly spherical Typical Eddy, which they claim induced the sweep, could result in a sweep which looked like a hand. Furthermore, one would expert the scale of the ejection to be comparable to the space between fingers, which again would be large compared to the scale directly observed by Corino and Brodkey. If the model were extrapolated to higher Reynolds number layers the ejection of wall layer fluid would certainly not be on a scale proportional to the wall layer units. Another fact that distracts from these "pressure" induced bursting models is that we do not expect the suddenness of the breakdown which was one of the characteristics agreed upon by the participants of the Stanford meeting, and also noted by Corino and Brodkey (1969).

It is interesting to note that Blackwelder does not feel that the pressure effect alone is enough to result in the burst, and thus ties it to the long streaky structure in the boundary layer, whereas Brodkey's group makes no reference to the need or existence of low speed streaks and rely solely on pressure and continuity. Blackwelder's free shear layer instability model requires oscillation and growth of oscillation as the first step in the evolution to breakdown, and thus may not include cases where short streamwise vortices appear immediately after liftup (Kim, Kline and Reynolds, 1968).

Another inner-outer layer interaction mechanism has been

proposed by Offen and Kline (1972,1975). They suggest that vortical motions which are seen in the log region induce a local adverse pressure gradient in the wall layer fluid below and just upstream. This adverse pressure gradient results in a local separation as seen by an observer moving with the vortex. It is interesting that this mechanism does not in principal require the existence of a low speed streak, although the adverse pressure gradient would be more effective in inducing the convected separation if it operated upon the low speed streak. Offen and Kline's inner-outer layer interaction is clearly not the direct result of a large scale sweep, but wallward moving fluid is required to bring the vortices close enough to the wall to produce a significantly strong adverse pressure gradient. Nychas, et al, (1973) proposed a vortex interaction which at first sight seems similar to that of Offen and Kline's, except that the transverse vortices of Nychas are in the outer layer (Typical Eddies further away from the wall) and their passage over the wall would at best produce a weak adverse pressure gradient near the wall. Nychas, et al, did not imply that the vortex moved towards the wall, whereas the vortices of Offen and Kline which induced lift-up did move towards the wall. Blackwelder and Woo (1974) by artifically applying a 3-D static pressure excitation, over a range of frequecies, at the edge of a turbulent boundary layer, were unable to effect the naturally occurring bursting frequency.

Finally, another model of inner-outer layer interaction has been proposed by Falco (1977a,b; 1978a,b). It involves the interaction of the vortex ring-like Typical Eddies with the wall. Those Typical Eddies which form in the inner part of the outer region will be convected towards the wall by the large scale sweeps. Falco (1977c,1978b) demonstrated that the sequence of events which results when a vortex ring intersects a wall at 5-10° (the angle at which sweeps have been observed to intersect the wall) is extremely similar to the bursting

sequence (Kline 1978), with the exception that it does not require the existence of the long sublayer streaks,and defintely involves short streamwise vortices. When the vortex ring approaches the wall, it sweeps out a pocket footprint below it (note discussion of wall region above), then induces fluid off the wall around the portion of the ring in closest contact with the wall. This fluid lifts up with the appearance of a hairpin. It is then induced laterally, part going towards one side of the ring, and part going towards the other side, and spirals up the sides of the vortex ring resulting in a counter-rotating tilted streamwise vortex pair that grows in diameter as it spirals up the remains of the vortex ring. This, of course, is a rapid mechanism for obtaining streamwise vorticity from the lifted wall layer fluid, which has high spanwise vorticity. At this stage, the picture closely resembles the double cone eddy of Townsend (1975) which he uses to predict intensity ratios and to point correlation shapes in the log region. Note that a basic inner region eddy must grow in scale proportional to y to be consistent with the log law scaling. The lower speed wall layer fluid spiraling upward around the side of the higher speed fluid comprising the vortex ring results in the close proximity of high and low speed fluid called the "two-layer"effect by Corino and Brodkey (1969) and noted by Kline (1978) and Willmarth (1977) using small hot-wires. When the wall layer fluid reaches the upper portion of the ring, which now appears as a horseshoe, the entire structure goes unstable and quickly breaksdown, resulting in a well mixed region which has the same sign of vorticity as the mean vorticity in the layer. In this regard it is of interest that Offen and Kline (1973) noted that "during the end of the bursts oscillatory growth stage, the interaction between the bursting fluid and the motion in the logarithmic region causes the formation of another large vortex-like structure."

This model requires the large scale sweep to bring the Typical Eddies to the wall, but sees the basic interaction to result from the instability of a viscous vortex ring with a

wall. Apart from being a mechanism which demonstratably results in lift-up of wall layer fluid, the mechanism proposed results in rapid breakdown. Although a viscous mechanism is responsible for the initial lift-up, the instability which occurs near the top of the former ring appears to be inviscid (essentially resulting from the interaction of two twisted vortex line elements), and this is inherently faster. Offen and Kline (1973) found that 80% of the breakups were directly caused by an interaction with another vortical structure. The importance of eddies of scale nearly equal 100 wall layer units interacting with the wall is demonstrated by wall pressure measurements which show that contributions to the wall layer units have approximately the same weight as the contributions of the large eddies. Since Typical Eddies are approximately 100 wall layer units over at least a decade in R_θ it appears that these pressure contributions may be due to their interaction with the wall.

One result of simultaneously measuring u, v, uv, $\partial u/\partial x$, $\partial v/\partial x$, $\partial u/\partial y$, ω_z and S_{xy} using a four wire probe, and the visual data in a light sheet parallel to the wall centered at $y^+ = 16$ and extending from $y^+ = 9$ to $y^+ = 23$ (Falco 1978b), has been confirmation of the picture that a large scale sweep at this location carries to the wall region disturbances which produce pockets that have very high uv associated with them, but that on the whole the large scale sweep is associated with little uv. This sweep has the apperance of Brodkey's hand where pockets have formed in between his fingers; i.e., the "active" regions of the large scale sweep, which I am assuming contained vortical Typical Eddies which the sweep convected toward the wall, quickly interacts with the wall leaving the inactive fingers he observed. This correspondence also explains the lift-up of wall layer fluid seen between the fingers, the short streamwise vortices seen there and the breakup observed there. Furthermore it incorporates the so-called "sweep" of Corino and Brodkey (1969) which they stressed swept away the ejection event and contributed little uv of its own. If the large scale sweep contains smaller scale "active" regions,

these would not be easily discriminated by hot-wire techniques based upon increases in the streamwise velocity fluctuations. large scale sweep can not have a significant uv contribution, it can, however, contain small scale regions of high uv.

One of the aspects where disagreement seemed strong was with respect to the sequence of events which occurred. Blackwelder (1978), Brodkey (1978), and Wallace, Brodkey and Eckelmann (1974), suggest that a fixed observer at $y^+ = 15$ would see an ejection followed by a large scale sweep. Offen and Kline (1973) and Lee, Eckelman and Hanratty (1974) suggest that the observer would see a sweep first, then the ejection. Falco (1978b) would agree with this later conclusion if the pocket flow module were being discussed. Of course, since the mechanism which causes a pocket is imbedded in a large scale sweep the observer will see a sweep after the sweep-burst sequence. This sweep-burst-sweep is similar to the sequence reported by Corino and Brodkey (1969). The situation with regard to the breakdown of the long streaky structure is not yet clear.

Most participants agreed that some sort of a sequence of events involving the burst cycle and the sweep events occurs, but there was disagreement over whether the cycle was inner dominated (Offen and Kline) or driven directly by the large scale motions (Blackwelder), or involved the Typical Eddy as an intermediary (Falco). Since the Typical Eddy forms at the upstream boundary of large scale motions (Falco 1977a), both Blackwelder's and Falco's bursting frequencies would scale on outer layer variables. If Offen and Kline are correct, bursting frequencies will scale on inner layer variables. Almost all of the evidence about "bursting" frequencies has been obtained using hot-wire anemometers. Subjective criteria must be used to decide when a "burst" is detected, and it certainly appears that these detectors cannot distinguish between different flow modules (for example the two described in the wall region). However, all the results suggest that the "bursts" scale on outer layer variables.

Finally, recent visual results of Praturi and Brodkey (1978) indicate that an inflection in the instantaneous velocity profile was the result of the ejections they observed, whereas Blackwelder's 1978 model depends on inflection in the instantaneous velocity profile to initiate his "free shear layer" instability mechanism. This apparent disagreement needs resolution. One possibility is that Blackwelder's detection technique finds the long streaky structure breakdown module, while Brodkey's visualization more readily sees the pocket flow module, but this is only speculation.

Conclusions

It is overwhelmingly clear that the three-dimensional nature of both wall layer and outer layer structural features plays an essential part in the dynamics of the boundary layer, and needs to be better understood.

Wall region needs further investigation. It is particularly important to make use of the technique of simultaneous flow visualization/hot-wire anemometry to tie together visual and anemometry results and to be able to distinguish between different flow modules in the wall region. The correspondence between various turbulence burst detectors (for example the Blackwelder and Kaplan (1976) scheme) the pattern recognition schemes (Brodkey, Wallace, Eckelman, 1974) and the elements of structure discussed is far from clear. The relative importance of the pocket flow module bursting seen by Falco (1977b, 1978a,b) and Smith (1978a,b) versus the long streaky structure bursting needs to be determined. The mechanisms for creation of either sequence are not yet fully understood. Whether or not past investigations have seen both processes and amalgamated them or whether given visual or anemometry techniques have selectively filtered out one of the flow modules needs to be discussed. On the whole there was no agreement (there certainly were suggestions, as noted earlier) as to what causes lifting, but the author feels that this may be the result of trying to make two different lift-up mechanisms fit one flow module, rather than recognizing

the existence of a double structure involved in the turbulence production process.

The formation of Typical Eddies in the outer region needs to be understood. The relationship, if any, between the large vortical region that results from the bursting process of Offen and Kline and the formation of Typical Eddies in the inner part of the outer region needs to be established. The vorticity associated with Typical Eddies and large scale sweeps as well as with the final stage of the bursting sequence needs to be measured for fundamental reasons as well as to allow modeling experiments of the physical (vortex ring/wall), analytical (Walker's theory) and numerical simulation types (see Moin, Reynolds, and Ferziger, 1978) to be compared. Although correspondence has been made between a compact vortical structure emanating from a turbulent wake and the formation of a pocket in a laminar boundary layer under the wake (Falco, 1978a), a direct correspondence between Typical Eddies in a boundary layer and the pockets in the inner region by simultaneous visualization is needed. (Recent work of Falco (unpublished) has shown the correspondence between Typical Eddies at the leading edge of a turbulent spot and pockets forming in the laminar boundary layer below the overhand.)

I have not discussed the theoretical contributions in this personal review and outlook although these need serious discussion. I do want to point out however that Landahl's (1978) theoretical model for creation of the Reynolds stress is an inviscid model which depends upon instability of a shear layer. It predicts a rapid breakdown at specific locations which results from the proposed focussing of small scale instability energy which can become phase locked to a large scale inhomogeneity. The experimentally observed rapid breakup of the oscillation/streamwise vorticity stage can possibly be modeled by a mechanism such as this. Walker's theory (see Doligalski and Walker, 1978) of the effect of a two-dimensional vortex moving over a wall focuses on the importance of viscosity in triggering an interaction of the vortex with the wall that

results in an eruption of fluid from the wall. The experiments of Falco (1977c) where a vortex ring was made to intersect a wall at a shallow angle, as noted earlier, definitely led to lift-up. The main point of Walker is that rotational flow in the outer layer gives rise to lift-up in the wall layer. So far his calculations cannot proceed far enough to determine what the interaction of this fluid with the higher speed flow into which it emerges is. These results will be interesting, although before detailed similarities can be expected, a computation involving a three dimensional vortex will be needed.

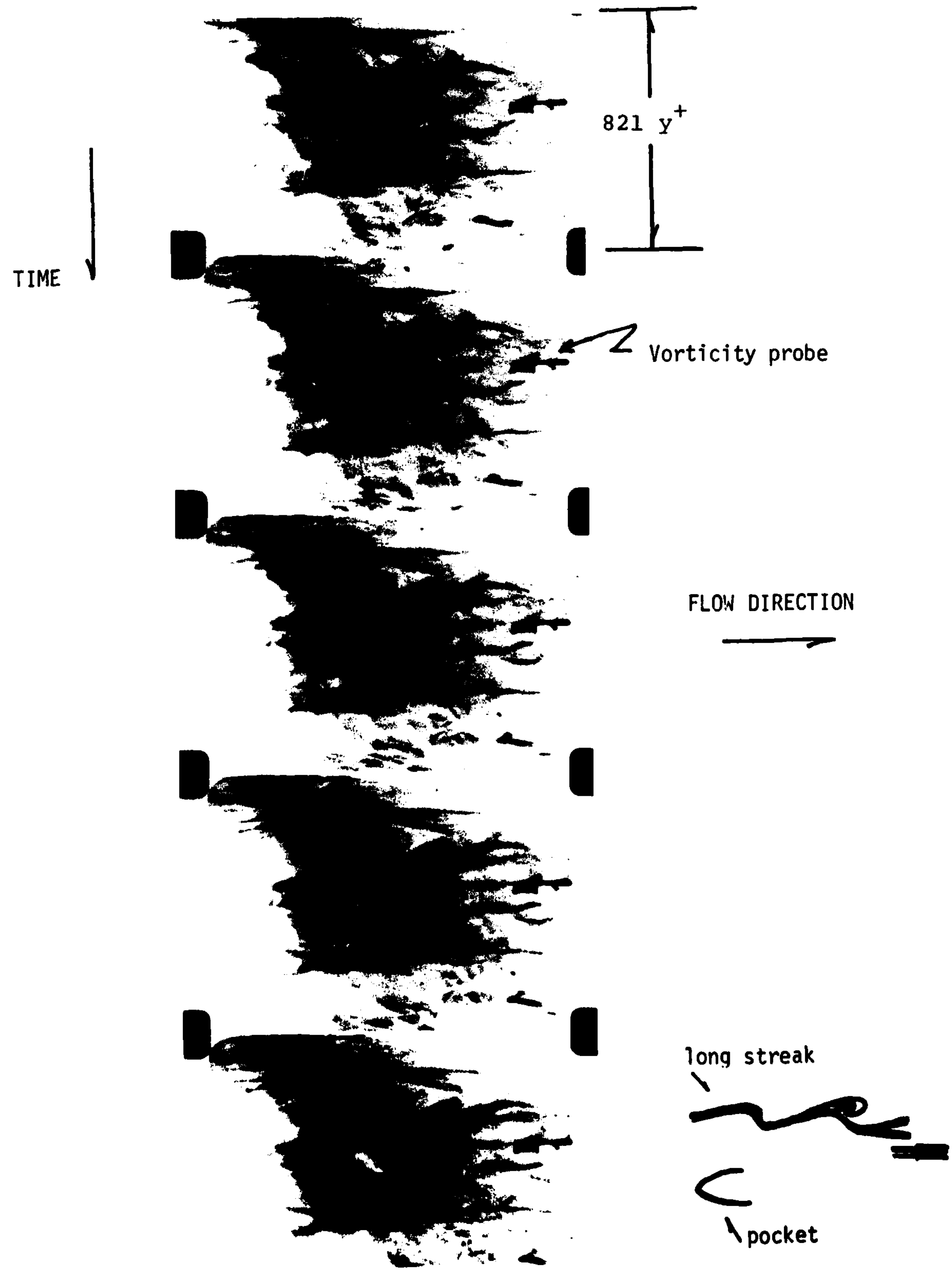
An area from which progress in understanding turbulence structure may well come is that of dilute polymer solution effects upon turbulence. It is hoped that some discussion of detailed structural changes will take place during the MSU workshop.

I want to put forth the hypothesis that the first phase of turbulent boundary layer structural investigations is near an end and the second phase has begun. By first phase, I mean that all of the half-blind investigations are no longer aimed at uncovering aspects of <u>one</u> characteristic coherent motion in the outer region, and one characteristic coherent motion in the wall region. In the outer region it is now clear that two different coherent motions, large scale motions and the Typical Eddies, need to be considered to understand the dynamics, and as I have suggested two different physical processes appear to be occurring in the inner region--this conclusion is new, and an important aspect of the MSU conference will be to debate this point. Of course, if the double structure in the sublayer is accepted, hand in hand with such an acceptance must go the fact that the visual impression made by both processes from lift-up through to mixing must be similar (a point made by Falco at the Stanford workshop), so that if one investigator was operating under ground rules which said that only one coherent sequence of events was behind the evolution in the wall region, they would be lumped together. Since Kim, Kline and Reynolds (1971) concluded that the bursting contributed

70% of the net production, the double structure hypothesis could only be valid if they could not distinguish between the lift-up, oscillation/streamwise vorticity, breakdown, and mixing stages that both the long streaky structure and the pockets undergo.

On the whole, it appears that a consistent picture, in the expanded framework suggested above may not be very far away.

Figure 1. Plan view of flow pattern in a sheet of laser light which is parallel to the wall. The thickness of the sheet is 14 wall layer units, and it is illuminating the flow between $y^+ = 9$ and $y^+ = 23$. The double structure in the sublayer is clearly seen, and both features are rapidly evolving in these five frames taken from a 16 mm movie. Sketches of a long streak which has undergone growing oscillations and breakdown, and of a pocket which has opened, have been made along side of the last frame. Once identified, the observer can trace their evolution in the preceding frames. A 4-wire cross-stream vorticity probe, centered at $y^+= 16$ can be seen in the left hand side of the frames. This is a negative print.



821 y+
TIME
Vorticity probe
FLOW DIRECTION
long streak
pocket

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